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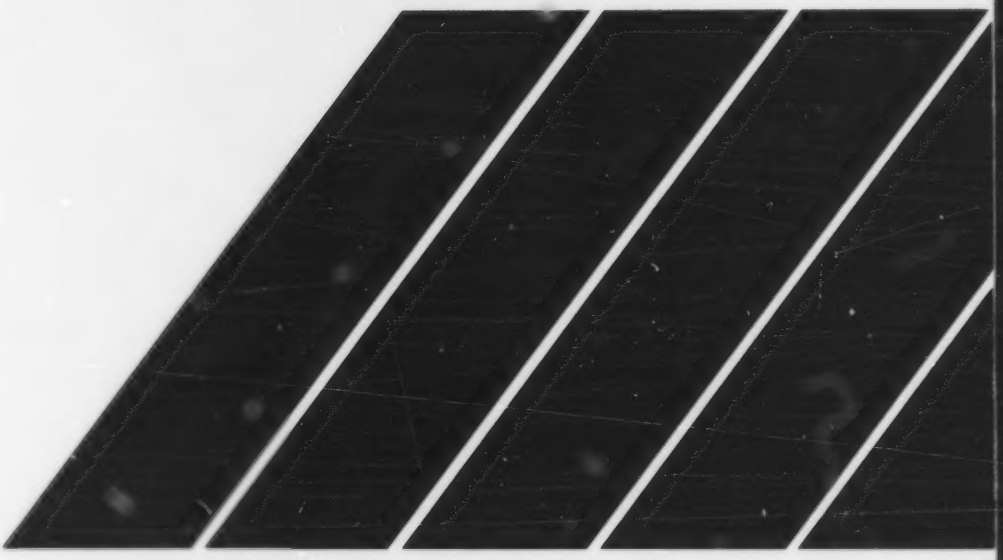
EVALUATION OF LIGHT NATURAL NAPHTHA AS FUEL FOR URBAN BUS TRANSPORTATION



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EVALUATION OF LIGHT NATURAL NAPHTHA AS FUEL FOR URBAN BUS TRANSPORTATION

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TABLE OF CONTENTS

		Page
RÉSUMÉ	.....	i
1. SUMMARY	.....	1
2. INTRODUCTION	.....	1
3. TEST DESCRIPTION	.....	3
3.1 Test Fuel Blending and Inspections	.....	3
3.2 Test Engine Description	.....	3
3.2 Emission Studies	.....	3
4. RESULTS	.....	6
5. DISCUSSION	.....	6
5.1 LNN Versus Diesel Exhaust Emissions	.....	6
5.2 Effect of Volatility of LNN on Emissions	...	7
5.3 Effect of Cetane Improver on Emissions	.....	8
5.4 Effect of Fuel Injection Timing on Emissions	...	8
5.5 Operational Problems with LNN Fuels	.....	9
5.6 EPA Heavy-Duty Diesel Transient Test	.....	9
6. CONCLUSIONS	.....	10
7. REFERENCES	.....	11

TABLES
APPENDICES

RÉSUMÉ

On a essayé du carburant diesel ordinaire et plusieurs carburants de naphta naturel léger (NNL), à bas point d'ébullition et faible teneur en aromatiques et en soufre, dans un moteur Cummins L-10 muni d'un système d'injection à commande électronique, au moyen d'un essai en régime permanent de mode AVL-8. Les résultats montrent que les NNL produisent moins de particules mais plus d'hydrocarbures supérieurs (HC) imbrûlés que le carburant diesel ordinaire.

On a étudié les effets des propriétés des carburants et du moment d'injection pour optimiser les émissions de gaz et de particules. Ainsi, le fait de faire passer la volatilité des NNL de 4,9 à 7,0 lb/po^2 de pression de vapeur Reid (PVR) n'a pas réduit les émissions de particules, mais le carburant plus léger (PVR 7) a produit plus de HC. De même, l'addition aux NNL de 1 % de nitrate de 2-éthylhexyle, un additif commercial qui augmente l'indice de cétane, n'a pas amélioré les émissions de gaz et de particules. En avançant un peu le moment de l'injection on diminuait les émissions de HC, mais on augmentait les émissions de NO_x sans améliorer les émissions de particules.

Des essais sur les émissions en phase transitoire avec du carburant diesel lourd EPA ont été commandés au Southwest Research Institute de San Antonio (Texas). Les émissions de particules étaient de 0,27 g/BHP.h et les émissions de HC très élevées à 20,5 g/BHP.h. Ces résultats montrent que le moteur Cummins L-10 avec injection à commande électronique n'est pas conforme aux normes d'émission des particules pour 1991 qui sont de 0,1 g/BHP.h ni à celles des émissions de HC qui sont de 1,3 g/BHP.h au maximum pour les autobus urbains utilisant du NNL comme carburant.

Il faut faire remarquer qu'en raison de la haute volatilité des NNL, les bouchons de vapeur étaient un grave problème par temps chaud, notamment à haute vitesse et en charge. Pendant toute l'étude, il a fallu maintenir le carburant à moins de 25 °C pour éliminer ce problème.

Ces résultats semblent indiquer que l'utilisation de NNL pour diminuer les émissions n'est pas prometteuse. Les moteurs devraient être modifiés pour empêcher les bouchons de vapeur et il faudrait un pot d'échappement catalytique pour réduire les émissions de particules et d'hydrocarbures.

1. SUMMARY

Regular diesel fuel and several low end-point, low aromatics and low sulphur light natural naphtha (LNN) fuels were tested in a Cummins L-10 engine equipped with electronic-controlled fuel injection system using the AVL 8-mode steady state test, and the results showed that LNN fuels produced less particulate and higher hydrocarbon (HC) emissions than conventional diesel fuel.

Both fuel properties and fuel injection timing changes were explored to optimize gaseous and particulate emissions. For example, increasing the LNN volatility from 4.9 to 7.0 psi of Reid Vapour Pressure (RVP) did not reduce particulate emissions, but the lighter fuel (7 psi RVP) was found to produce more HC emissions. Similarly, treating the LNN fuel with 1% of 2-ethylhexyl-nitrate (DII), a commercially available cetane improver, did not improve gaseous or particulate emissions. Advancing the fuel injection timing slightly improved HC emissions, but NO_x emissions were adversely affected. Changing the fuel injection timing also showed no improvement in particulate emissions.

An EPA heavy-duty diesel transient emissions test was subcontracted to Southwest Research Institute in San Antonio, Texas. The particulate emissions were found to be 0.27 g/BHP-Hr, and the HC emissions were very high at 20.5 g/BHP-Hr. The results show that the Cummins L10 engine with electronic-controlled fuel injection does not meet the 1991 particulate emissions regulation of less than 0.1 g/BHP-Hr and HC emissions of less than 1.3 g/BHP-Hr for urban bus application with the LNN fuel.

It should be pointed out that because of the high front-end volatility of the LNN fuel, severe vapour-lock problem was observed at warm ambient conditions, particularly under high speed and high load operations. Throughout this study, it was found necessary to cool the fuel down to below 25°C in order to eliminate this vapour-lock problem.

These results suggested that the development of LNN as a low emission bus fuel does not appear very attractive. Engine hardware modifications will be necessary to overcome the vapour-lock problem and an exhaust catalyst needed to reduce particulate and hydrocarbon emissions.

2. INTRODUCTION

The Canadian Government is now developing exhaust emission regulations for heavy duty diesel engines for the 1990's. Since December 1, 1988 Canada has already legislated heavy duty diesel exhaust emissions, and the standards are in fact equivalent to the 1990 U.S. standards(1) (Table 1).

In the U.S., both particulate and NO_x emissions will be tightened in 1991 (Table 1), and especially the allowable particulate emission level will be substantially reduced from 0.6 g/BHP-Hr to 0.25 g/BHP-Hr for heavy duty truck applications. Since the primary concern for particulate emissions are their associated health hazard, the U.S. had proposed an even further reduction of particulate emissions to 0.1 g/BHP-Hr in 1991 for urban buses, because the emissions produced by the diesel engines under this type of operation would impose significantly greater health threats to the general public than highway trucks. By 1994, even the heavy duty diesel engines for truck application will have to meet this very stringent particulate emission requirement.

In order to meet the proposed lower emission standards, engine manufacturers have been developing new engine technology for cleaner combustion(2,3). In addition, many studies have shown that diesel fuels with lower sulphur, aromatics and end point might benefit these new engines in meeting lower emission standards(4-8). In fact, U.S. EPA is proposing a 0.05% sulphur and 40% cetane index diesel fuel for 1993.

Both the U.S. and the Canadian oil industries have indicated that significant reductions in the sulphur and aromatic levels in diesel fuels will be extremely costly. However, since the volume of diesel fuel for urban bus use only represent a relatively small proportion of the total diesel fuel sold in Canada, an alternate fuel could be a viable approach; and Detroit Diesel is seriously considering methanol bus engines.

With lead scheduled to be phased out at the end of 1990, large volumes of LNN, which cannot be accommodated in the mogas pool because of its low octane number (~50), become available. Another outlet for LNN, which is Turbo B, is also rapidly declining due to safety and supply reasons resulting in a switch to kerosene jet fuel by the civil and the military aviation bodies. LNN, which is a straight run refinery stream and comprises mainly isomers of pentane and hexane, is very low in aromatics and sulphur. Typical compositions and properties of two LNN streams are shown in Table 2, and their cetane numbers are predicted to be reasonably high. Based on the properties of LNN, it is reasonable to predict that LNN might be a suitable replacement for diesel fuel and could produce much less particulate emissions. Initial results to-date have been encouraging, for example, in a Detroit Diesel 6V71 engine, it gave a 50% reduction in particulates versus a conventional #2 diesel fuel, although HC emissions were found to be higher when using LNN. It was felt that both particulates and HC emissions could be reduced if the injection timing and volume were optimized in a more modern engine. Increasing the cetane number of the fuel might also help to further minimize emissions. High injector wear was also identified in our earlier study, due to the very low viscosity of LNN, but the problem was well controlled with the help of a commercially available lubricity additive.

The objective of this project is to demonstrate the feasibility of using light natural naphtha (LNN) as a diesel fuel for urban buses to control the gaseous and particulate emissions to a level meeting the 1991 U.S. proposed standards for buses. The demonstration will consist of optimizing a Cummins L-10 diesel engine to run on clear and additized LNN, and measuring the emissions levels produced under various steady state and the EPA transient test conditions.

Based on the above objective, a four month contract, which was partly funded by the Ministry of Energy, Mines and Resources Canada, was awarded to Esso Petroleum Canada. This document is the final report that presents and discusses all the emission data obtained from testing the Cummins L-10 engine with the various light natural naphtha fuels.

3. TEST DESCRIPTION

3.1 Test Fuel Blending and Inspections

Ten barrels of regular No. 2 diesel were acquired for this program. They were used periodically to check the baseline performance of the engine. Its properties are summarized in Table 2.

Three different LNN cuts were obtained from Dartmouth Refinery, and their inspections are summarized in Table 3. Samples L and M have similar boiling ranges and their Reid Vapour Pressures (RVP) are 3.4 psi and 4.9 psi, respectively. Sample H, on the other hand, has very different boiling range and a very high RVP of 15 psi. Samples H and L were in fact used to blend a 7 RVP fuel to examine the effect of volatility on emission as well as performance. Its properties are also summarized in Table 3.

Two ignition-improved LNN fuels were also prepared by adding 1% and 3%, respectively, of 2-ethylhexylnitrate in Sample M (4.9 RVP).

3.2 Test Engine Description

The test engine is a Cummins L-10 in-line 6 cylinder turbocharged and aftercooled engine. It is a 4-cycle engine with a compression ratio of 16.3:1. It has a 10 L displacement and is equipped with Cummins ECI Electronic Fuel System which will allow variation in the fuel injection timing.

3.3 Emission Studies

3.3.1 Bench Engine Set-Up

The Cummins L-10 engine was set-up at the engine test laboratory of Esso Petroleum Canada Research Department. A Schenck Dynamometer W400 and Dyno Controls Digalog Model 1022 were used to control the engine RPM and torque, as measured by RPM magnetic pick-up (North American Phillips Controls Airpax #876) and Lebow load cell (#3169), respectively. Other engine operating parameters, such as intake-air temperature and pressure, oil, coolant, fuel and exhaust temperatures, were also measured.

3.3.2 Gaseous and Particulate Emission Measurements

The schematic of the gaseous and particulate sampling system is shown in Figure 1. All the instrumentations used in the exhaust sampling system are summarized in Table 4. The engine intake-air for combustion was supplied by a constant RPM blower rated at 3000 CFM. This blower also supplied sufficient air to dilute all the engine exhaust to about 191°C (375°F) in the primary dilution tunnel. A mass flowmeter was used to measure the total mass flow of air to the engine intake and the primary dilution tunnel. It is a very good approximation, especially under lean-burn conditions, that the mass flow of engine intake air

per unit time is equivalent to the mass flow of its exhaust gas. Since the primary (1°) diluted exhaust flow rate is expressed in lb/min, and the gaseous emission concentrations in the 1° diluted exhaust were measured as volume ppm, the weight of the gaseous emissions in g/hr are expressed by the following equations:

$$\text{HC (g/hr)} = \frac{MF(1°) \times 60 \times 453.59 \times HC\ (ppm) \times 0.5768}{1.2047 \times 1{,}000{,}000}$$

$$\text{CO (g/hr)} = \frac{MF(1°) \times 60 \times 453.59 \times CO\ (ppm) \times 1.1647}{1.2047 \times 1{,}000{,}000}$$

$$NO_x\ \text{(g/hr)} = \frac{MF(1°) \times 60 \times 453.59 \times NO_x\ (ppm) \times 1.913}{1.2047 \times 1{,}000{,}000}$$

where MF (1°) = Mass Flowrate in 1° Tunnel in lb/min.

In order to sample particulate at temperatures less than 125°F (~51°C), a two-stage dilution (double dilution) was used. A particulate sampling blower, rated at 20-120 CFM, was used to pull a sample of diluted exhaust from the 1° tunnel into the secondary (2°) tunnel and additional dilution air was also simultaneously pulled in to further dilute the exhaust gas. A pair of 90 mm T60A20 Pall Flax filters were used to filter the particulates from the 2° diluted exhaust for weighing, and the weight of the particulates in g/hr is expressed by the following equation:

$$\text{Particulate (g/hr)} = \frac{Wt \times 60 \times MF\ (1°)}{[MF\ (3) - MF\ (2°)] \times S \times 1000}$$

where Wt = Weight of Particulates Collected in mg
MF (1°) = Mass Flowrate in 1° tunnel in lb/min
MF (2°) = Flowrate of 2° dilution air into 2° tunnel in lb/min
MF (3) = Flowrate of the particulate sampling blower in lb/min
and S = Particulate sampling time in min.

In the present study, the AVL 8 mode test was used to simulate the EPA Heavy-Duty Diesel Transient Test(9). Basically, the test involved measuring the gaseous and the particulate emissions under eight steady state operating conditions, and the "Transient Emissions" are calculated from the weighted averages of the 8-modes' emissions.

In order to run this AVL 8 mode test, it is necessary to determine the maximum torque at various RPMs, because the operating conditions of the 8-mode test are specified as percent maximum torque at various RPM (see Table 5). The 0% torque and 0% RPM in mode 1 represent engine idling at 650 RPM. In the present study, a very light load of 50 N-m has to be applied in order to achieve smooth idling. 100% RPM in mode 5 represents the RPM at rated hp. The actual RPM for the other modes are then obtained as follows:

Actual RPM = Rated RPM - (Rated RPM - Idle RPM) (100 - % RPM)

After obtaining the actual RPMs from mode 2 to 8, the maximum torque at these various RPMs were determined, and the actual torque for each mode is in fact the % maximum torque at that given RPM. All the actual RPM and actual torque for the 8 modes are summarized in Table 5.

The BHP-Hr for the 8-modes were also calculated using the following equation, and they are also summarized in Table 5:

$$\text{Modal BHP-Hr} = \frac{1.341 \text{ (Actual RPM) (Actual Torque in N-m)}}{9550}$$

After measuring the gaseous and particulate emissions for all the 8-modes, the overall EPA transient emissions are calculated as follows:

$$\text{Emission (in g/BHP-Hr)} = \frac{\Sigma \text{ (WF}_n \text{ Emission}_n)}{\Sigma \text{ (WFn BHP}_n)}$$

where Emission_n - Either HC, CO, NO_x or Particulate in g/hr for the nth mode
WF_n - Weighing Factor for the nth mode
and BHP_n - Brake Horse Power for the nth mode

3.3.3 Engine Testing Procedure

All the emission testing was done with the Cummins L-10 engine fully warmed up with the test fuel. All the gaseous analyzers were calibrated daily prior to the test. The exhaust emission sampling system was turned on at least half an hour prior to a test to ensure stable operation. All the gaseous emissions were monitored continuously.

At the junction of the 1° and the 2° dilutions tunnel, an electrically-operated valve was installed to by-pass the exhaust gas when the particulate sampling blower was equilibrating. Two pairs of pre-weighed filters were also mounted in the particulate housing during the equilibration process to minimize sudden pressure change when the valve was opened to start particulate sampling.

The engine usually reached stable RPM and torque very quickly, especially when the engine oil and coolant were also fully warmed up (Table 6). In changing from one mode of operation to the other, again the engine RPM and torque stabilized very quickly, but the exhaust gas temperature in the 1° dilution tunnel usually required about half an hour to stabilize.

Particulate sample would commence when the exhaust gas temperature in the 1° dilution tunnel had stabilized. In general, for the 8 different modes of operation, about 5-15 minutes of sampling were adequate enough to collect >5 mg of particulates for weighing.

During all the emission tests, the fuel temperature was maintained at <25°C to suppress "vapour-lock" problem at the fuel pump (to be discussed).

4. RESULTS

As mentioned earlier, this Cummins L-10 engine is equipped with electronically-controlled fuel injectors. The fuel injection timing can be easily changed by re-programming the Electronic Control Module.

It should be pointed out that the fuel injection timing described in this report is actually the timing for the closure of the injector control valve. When this injector control valve is closed, pressure inside the fuel metering chamber would build up until it is high enough to force open the needle valve for injection to occur.

The 8-mode emission test was carried out with the diesel fuel at the start and at the end of this program with fuel injection timing set to the 'optimum' diesel timing (Cummins Proprietary information). All the results are summarized in Appendices 1 and 2. The overall gaseous and particulate emissions are shown in Table 7, and it can be seen that the two tests have very good repeatability, suggesting that the baseline performance of the engine and the equipments have not drifted during the course of this program.

For all the LNN testing, three sets of fuel injection timing were used and they are summarized in Table 8. The "standard" fuel injection timing for the LNN operation was again provided to Esso by Cummins Engine Ltd. A total of 4 LNN fuels were tested (2 with RVPs of 4.9 and 7.0 psi and the 2 were the 4.9 RVP fuel with either 1% or 3% 2-ethylhexylnitrate) under the 3 different fuel injection timings; and all the results are summarized in Appendices 3 to 17.

Again, using the weighing factors for the individual modes (Table 5) and the equation as shown in Section 3.3.2, the overall EPA transient emissions results were calculated, and they are summarized in Tables 9 to 12.

5. DISCUSSION

5.1 LNN versus Diesel Exhaust Emissions

The overall emissions for the LNN (4.9 RVP) and the diesel fuel are shown in Table 13. It can be seen that diesel fuel produced relatively less hydrocarbon (HC) emissions than the light LNN (4.9 RVP). The high hydrocarbon emissions could be due to the high volatility of the LNN fuel and also its low ignition quality. Previous study has shown that LNN probably has cetane number of about 30, and this was estimated from the cetane numbers of various diesel/LNN blends. High fuel volatility could sometimes lead to higher hydrocarbon emissions because the residual fuel inside the tip of the fuel injector will be easier to vaporize out into the combustion chamber during the expansion stroke.

Both diesel and LNN produced very low levels of CO emission at 2.5 g/BHP-Hr, and this is significantly below the 15.5 g/BHP-Hr level required by the proposed 1991 regulation.

The NO_x emissions for the two fuels were also very similar (2.9 and 3.0 g/BHP-Hr for diesel and LNN, respectively). Since NO_x is primarily formed between nitrogen and oxygen in the high temperature combustion zone, it was not too surprised to find that both fuels produced similar NO_x emissions because at the same engine power output, their exhaust temperatures were very similar (see Appendices 1 to 8).

The total particulate emissions from diesel fuel averaged at 0.28 g/BHP-Hr. At this stage, it is not clear whether this Cummins L-10 engine with electronic-controlled fuel injection would be able to meet the 1991 regulated 0.25 g/BHP-Hr level, since the above result was based on the steady state 8-mode test and the ultimate certification test is the EPA heavy-duty diesel transient test.

With the LNN (4.9 RVP) fuel, the total particulate emissions were significantly reduced by about 30% to 0.19 g/BHP-Hr. This reduction is consistent with the lower aromatic and sulphur levels in the LNN fuel relative to those in the diesel fuel (c.f. Tables 2 and 3).

5.2 Effect of Volatility of LNN on Emissions

One of the major concerns about LNN is its safety in storage, particularly in a vehicle fuel tank. The concern here is the flammability of the vapour space inside the vehicle fuel tank under normal ambient operating conditions. For regular diesel fuel, the RVP would be too low and the vapour would then be too lean for combustion to take place. On the other hand, mogas would generally have higher than 8 RVP and the vapour would correspondingly be too rich to burn. Unfortunately, LNN has RVP values in between those of mogas and diesel; and increasing the RVP of the LNN fuel to that of commercial gasoline would certainly alleviate this safety concern.

A 7 RVP LNN, with slightly higher front end volatility than the 4.9 RVP LNN (see Table 2), was tested, and the results are shown in Table 10. At standard fuel injection timing, the gaseous and particulate emissions produced from this more volatile (7 RVP) LNN fuel are compared with those produced from the 4.9 RVP fuel as shown in Figure 2. Results clearly suggested that increasing the RVP of the LNN fuel did not improve particulate emissions and in fact significantly increase HC emissions.

In Figure 2, the gaseous and particulate emissions for the 4.9 RVP and the 7 RVP LNN fuels under retarded and advanced fuel injection timing were also plotted. The effect of fuel injection timing on emissions will be discussed later in this report. Nevertheless, it can be seen in Figure 2 that the 7 RVP LNN fuel produced more HC emissions than the 4.9 RVP LNN fuel under the retarded and the standard fuel injection timing conditions. Interestingly, the CO emissions were slightly increased with increase fuel volatility under all three different fuel injection timing conditions. NO_x and particulate emissions, on the other hand, were unaffected by fuel volatility.

5.3 Effect of Cetane Improver on Emissions

Due to the low ignition quality of LNN, high dosages of 2-ethylhexyl-nitrate (1% and 3% of DII) were added to the 4.9 RVP LNN fuel, and both fuels were tested under all 3 different fuel injection timings. All the results are summarized in Tables 11 and 12, and graphically represented in Figure 3.

The effect of DII on HC emissions are not clearly understood. For the 4.9 RVP LNN fuel and the same LNN fuel containing 1% DII, there was no measurable effect on HC emissions (both fuels showed about 1.4-1.5 g/BHP-Hr of HC emissions). At 3% DII treat, the HC emissions were reduced to 1.1 g/BHP-Hr. In general, for diesel fuel with relatively low cetane number, increasing the cetane number via the use of cetane improver would reduce HC emissions due to more complete combustion as a result of shorter ignition delay leading to longer combustion duration. In the case of the LNN fuel, HC emission could be primarily due to vaporization of the residual fuel left inside the injector tip, and therefore using 1% DII to reduce ignition delay did not show any major HC reduction.

In fact, this reduced ignition delay could very well explain the reduced CO emission for the two DII-treated LNN fuels, as shown in Figure 3.

The two DII-treated LNN also produced similar NO_x emissions to the untreated fuel.

For the LNN fuel treated with 1% DII, there did not appear to be any effect on particulate emissions. However, for the fuel treated with 3% DII, there was a significant reduction of particulate emissions from about 0.20 to 0.13 g/BHP-Hr.

5.4 Effect of Fuel Injection Timing on Emissions

In this report, the emission data obtained from the 4.9 RVP LNN fuel were used to illustrate the effect of fuel injection timing on gaseous and particulate emissions (see Figure 4). In general, the fuel injection timing has the same effects on the other LNN fuels as well (c.f. Figures 2 and 3).

Advancing the injection timing, in general, resulted in reduction in the HC emissions. This was probably due to more premixed combustion resulting in slightly more complete combustion. The same argument can probably be applied to explain the slight reduction in CO emissions with advanced fuel injection timing. It can also be seen from Figure 2 that the more volatile 7 RVP LNN fuel showed the same effects.

It is interesting to point out that the two DII-treated LNN fuels did not clearly show HC and CO reduction with advanced injection timing. It is probable that this premixed combustion effect was somewhat curtailed by the shorter ignition delay for these two DII-treated LNN fuels.

For all the LNN fuels tested, advanced injection timing resulted in increased NO_x emissions, and this is consistent with increased premixed combustion.

Particulate emissions, on the other hand, appeared to be unaffected by changes in the fuel injection timing.

5.5 Operational Problems with LNN Fuels

One of the major problems associated with the use of LNN fuel appears to be fuel pump vapour-locking. This problem is particularly severe under high ambient temperatures.

The LNN fuels have significantly higher front-end volatility than any Type A and Type B diesels. With the fuel pump being mounted onto the engine block, there was a lot of heat transferred to the fuel pump when the engine was fully warmed up. In the case of the Cummins L-10 engine, the fuel was also used to cool the fuel injectors, and there was a lot of "hot" fuel returning from the fuel injectors into the fuel tank. In fact, under high torque and low speed operations, the fuel tank temperature could reach about 50°C.

When the fuel temperature was high and the fuel pump was hot, engine surging was observed especially under high speed operations. Since the fuel pump is gear-driven and at high engine RPM the pump would have to pump more fuel through the system, thereby generating a higher pressure across the pump, it appeared that the light fuel was vaporized at the suction side of the pump causing "temporary" fuel starvation resulting in unstable engine speed.

Throughout this study, it was found that it was necessary to cool the fuel down to below 25°C to eliminate this engine surging problem.

5.6 EPA Heavy-Duty Diesel Transient Test

The EPA heavy-duty diesel transient test was subcontracted to Southwest Research Institute in San Antonio. The Cummins L10 engine was set up to identical fuel injection timing and pressure as the L10 engine in Esso Petroleum Canada Research, and the 4.9 RVP LNN was tested.

The engine had a great deal of difficulty running the cold cycle; it misfired a lot and failed the regression standard set by EPA.

The emission results for the cold and the hot start cycles, as well as the composite transient test, are summarized in Table 14. In comparison with the steady-state (8-mode test) emission data shown in Table 9, the transient HC emissions were about 14 times, the transient CO emission was about 4 times and the transient NO_x emissions were about 2 times higher than steady-state data. The transient particulate emissions were also about 42% higher than the steady-state emission (0.27 versus 0.19 g/BHP-hr). Prior to 1984, a 13-mode steady-state test was used for gaseous emission testing, and this has since changed to transient engine dynamometer testing to allow for particulate measurement. Therefore, there was very little literature data available on the comparison of steady-state and transient emissions. In general, the transient gaseous and particulate emission levels were relatively higher than those obtained under steady-state test due to to the occurrence of rich fuel-air cycles during the transient test(7,10,11).

In a study carried out by AVL(9) using two 11L direct injection/ turbochanged six-cylinder engines, the transient particulate emissions were about 16-20% higher than the steady-state particulate emissions. In the present study with the Cummins L10 engine using LNN fuel, the transient particulate emissions were about 42% higher than steady-state particulate emissions. It appears that the particulate mass emissions can be significantly affected by interaction between the properties of the fuel burned, the engine design and the transient operation; and it is beyond the scope of this present study to arrive at any explanation.

The transient data showed that the Cummins L10 engine with electronically-controlled fuel injection did not meet the 1991 particulate emissions regulation of less than 0.1 g/BHP-Hr and HC emissions of less than 1.3 g/BHP-Hr for urban bus application even with the LNN fuel.

6. CONCLUSIONS

Regular diesel fuel and several low end-point, low aromatics and low sulphur light natural naphtha (LNN) fuels were tested in a Cummins L-10 engine equipped with electronic-controlled fuel injection system. The hydrocarbon (HC), carbon monoxide (CO), nitrogen ides (NO_x) and particulate emissions were measured using the AVL 8-mode test under three different sets of fuel injection timings, and the following conclusions were reached:

(i) LNN produced less particulate emissions than conventional diesel, but HC emissions were relatively higher than that of diesel.

(ii) Increasing the RVP of LNN from 4.9 to 7 psi did not reduce particulate emissions, but the lighter fuel was found to produce more HC and CO emissions.

(iii) Use of 2-ethylhexylnitrate (DII) at 1-3% treat in LNN reduced CO emission. At 1% DII treat, HC, NO_x and particulate emissions were not affected. However, at 3% DII treat, HC and particulate emissions were reduced.

(iv) In general, advanced fuel injection timing reduced HC emissions, but NO_x emissions were increased.

(v) Advancing or retarding the fuel injection timing did not affect particulate emissions.

(vi) Severe vapour-lock problem occurred at warm ambient temperatures, particularly under high speed and high load operations.

An EPA heavy-duty diesel transient test was also subcontracted to Southwest Research Institute in San Antonio, Texas; and the particulate and HC emissions were found to be 0.27 g/BHP-Hr and 20.5 g/BHP-Hr, respectively. The results showed that the Cummins L10 engine with electronic-controlled fuel injection did not meet the 1991 particulate emissions regulation of less than 0.1 g/BHP-Hr and HC emissions of less than 1.3 g/BHP-Hr for urban bus application even with the LNN fuel.

7. REFERENCES

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(6) "Fuel Composition Effects on Heavy-Duty Diesel Particulates Emissions", J.C. Wall and S.K. Hoekman, SAE 841364.

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TABLE 1

U.S. HEAVY DUTY DIESEL EMISSION REGULATIONS

	1985-87	1988-1989	1990	1991-1993	1994
HC (g/BHP-Hr)	1.3	1.3	1.3	1.3	1.3
CO (g/BHP-Hr)	15.5	15.5	15.5	15.5	15.5
NO_x (g/BHP-Hr)	10.7	10.7	6.0	5.0	Reserved
Particulates (g/BHP-Hr)	No Regulation	0.6	0.6	0.25 (Trucks) 0.1 (Buses)	0.1 (Trucks and Buses)

- Canada adopted 1990 U.S. regulation as of December 1, 1988.

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TABLE 2

L-10 REFERENCE DIESEL FUELS INSPECTIONS

Density, g/cc	0.8439
Sulphur, wt%	0.30
Flash Pt., °C	53.0
Viscosity, cSt @ 40°C	1.93
Aniline Pt., °C	53.0
Cloud Pt., °C	-24
Colour, ASTM	0.05
D-86, °C	
IBP	158
5	177
10	185
20	202
30	215
40	229
50	241
60	253
70	263
80	277
90	297
95	320
FBP	329
FIA A%	35
O%	0.0
S%	65

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TABLE 3

PROPERTIES OF THE LNN FUELS

	L	M	H	7 RVP
RVP, psi	3.4	4.9	15.0	7.0
Density, kg/L at 15°C	0.7290	0.7091	0.6617	0.7134
Flash Pt., °C	<0	<0	<0	<0
Sulphur, ppm	11.0	4.9	4.9	9.9
Viscosity, cSt at 40°C	0.52	0.51	0.36	0.49
FIA Aromatics %	8	6	3	5
Olefins %	1	1	0	1
Saturates %	91	93	97	94
Aniline Pt., °C	48.4	54.2		51.6
D-86 IBP °C	73	64	27	42
10	80	73	37	64
30	83	74	42	71
50	87	76	47	78
70	93	80	55	86
90	110	95	69	101
FBP	128	137	85	123

* All LNN test fuels contained 25 ppm Hitec 515 as lubricity additive.

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TABLE 4

INSTRUMENTATION USED IN THE EXHAUST EMISSION SAMPLING SYSTEM

	Applications	Instrument Description
1.	Air Supply to Engine and 1° Tunnel	Curtis CR-850 Blower rated at 3000 CFM
2.	Withdraw Exhaust for Particulate Sampling	Spencer RBL-10 Blower rated at 20-120 CFM
3.	Mass Flowmeter for Engine Intake Air and 1° Dilution Air	FCI LT81A-4 Flowmeter
4.	Flowmeter for 2° Dilution Air	EG&G Flow Technology TWA-C-6 Turbine Meter
5.	Flowmeter for 2° Dilution Air and 1° Diluted Exhaust	EG&G Flow Technology TWA-C-6 Turbine Meter
6.	Primary (1°) Dilution Tunnel	12" ID x 12' Length
7.	Secondary (1°) Dilution Tunnel	3" ID x 3' Length
8.	Hydrocarbons Measurement	Beckmann Model 402 Hydrocarbon Analyzer
9.	Carbon Monoxide Measurement	Beckmann Model 865 Infrared Analyzer
10.	Carbon Dioxide Measurement	Beckmann Model 864 Infrared Analyzer
11.	Nitrogen Oxides Measurement	Thermo Electron Model 10AR NO/NOX Meter

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TABLE 5

CUMMINS L-10/LNN 8 MODE TEST CONDITIONS

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
% Torque	0	25	63	84	18	40	69	95
Actual Torque (N-m)	50	200	615	861	155	380	644	927
% RPM	0	11	21	32	100	95	95	89
Actual RPM	650	782	932	1105	2071	2024	2024	1936
Weighting Factor	35.01	6.34	2.91	3.34	8.40	10.45	10.21	7.34
BHP-Hr	4.6	22.0	80.5	133.6	45.1	108.0	183.0	252.0

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TABLE 6

L-10 ENGINE OPERATING TEMPERATURES (°C) - 8 MODE TEST

Mode	Clnt In	Clnt Out	Oil	Fuel	Exhaust
1	47	78	84	18	126
2	47	79	88	19	210
3	48	83	97	19	443
4	50	85	105	20	527
5	47	82	99	24	241
6	50	83	104	22	329
7	50	85	113	20	387
8	51	88	115	19	441

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TABLE 7

OVERALL EMISSION SUMMARY FOR DIESEL FUEL

Emittants	Overall Emission (g/BHP-Hr)
HC	0.4; 0.6
CO	2.5; 2.5
NO_x	2.9; 2.8
Particulates	0.29; 0.27

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TABLE 8

FUEL INJECTION TIMING FOR LNN TESTING

Mode	Fuel Injection Timing °BTDC		
	Retard	Standard	Advanced
1	30	35	40
2	30	35	40
3	30	35	40
4	30	35	40
5	27	32	37
6	20	25	30
7	20	25	30
8	20	25	30

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TABLE 9

OVERALL EMISSION SUMMARY FOR LNN (4.9 RVP) FUEL

Emittants	Overall Emissions (g/BHP-Hr) Retarded Timing	Standard Timing	Advanced Timing
HC	1.3; 1.6	1.3; 1.6	1.3; 1.4
CO	2.4; 2.8	2.3; 2.6	2.3; 2.7
NO_x	2.8; 2.6	3.0; 2.9	3.2; 3.1
Particulate	0.19; 0.18	0.20; 0.18	0.21; 0.19

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TABLE 10

OVERALL EMISSION SUMMARY FOR LNN (7 RVP) FUEL

Emittants	Overall Emissions (g/BHP-Hr) Retarded Timing	Standard Timing	Advanced Timing
HC	1.7	1.7	1.3
CO	2.9	2.7	2.7
NO_x	2.8	3.1	3.2
Particulate	0.19	0.20	0.20

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TABLE 11

OVERALL EMISSION SUMMARY FOR LNN (4.9 RVP + 1% DII) FUEL

Emittants	Overall Emissions (g/BHP-Hr) Retarded Timing	Standard Timing	Advanced Timing
HC	1.4	1.5	1.4
CO	1.8	1.7	1.8
NO_x	2.6	3.1	3.4
Particulate	0.17	0.19	0.22

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TABLE 12

OVERALL EMISSION SUMMARY FOR LNN (4.9 RVP + 3% DII) FUEL

Emittants	Overall Emissions (g/BHP-Hr) Retarded Timing	Standard Timing	Advanced Timing
HC	1.1	1.1	1.1
CO	1.7	1.7	1.8
NO_x	2.6	3.0	3.1
Particulate	0.13	0.12	0.13

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TABLE 13

LNN VERSUS DIESEL EXHAUST EMISSION

	Diesel	LNN (4.9 RVP)
HC	0.5	1.5
CO	2.5	2.5
NO_x	2.9	3.0
Particulate	0.28	0.19

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TABLE 14

EMISSION DATA FOR THE L10/LNN TRANSIENT TEST

	Cold	Hot	Transient
HC (g/BHP-Hr)	34.0	18.3	20.5
CO (g/BHP-Hr)	15.9	9.4	10.4
NO_x (g/BHP-Hr)	7.1	5.6	5.8
Particulate (g/BHP-Hr)	0.42	0.24	0.27

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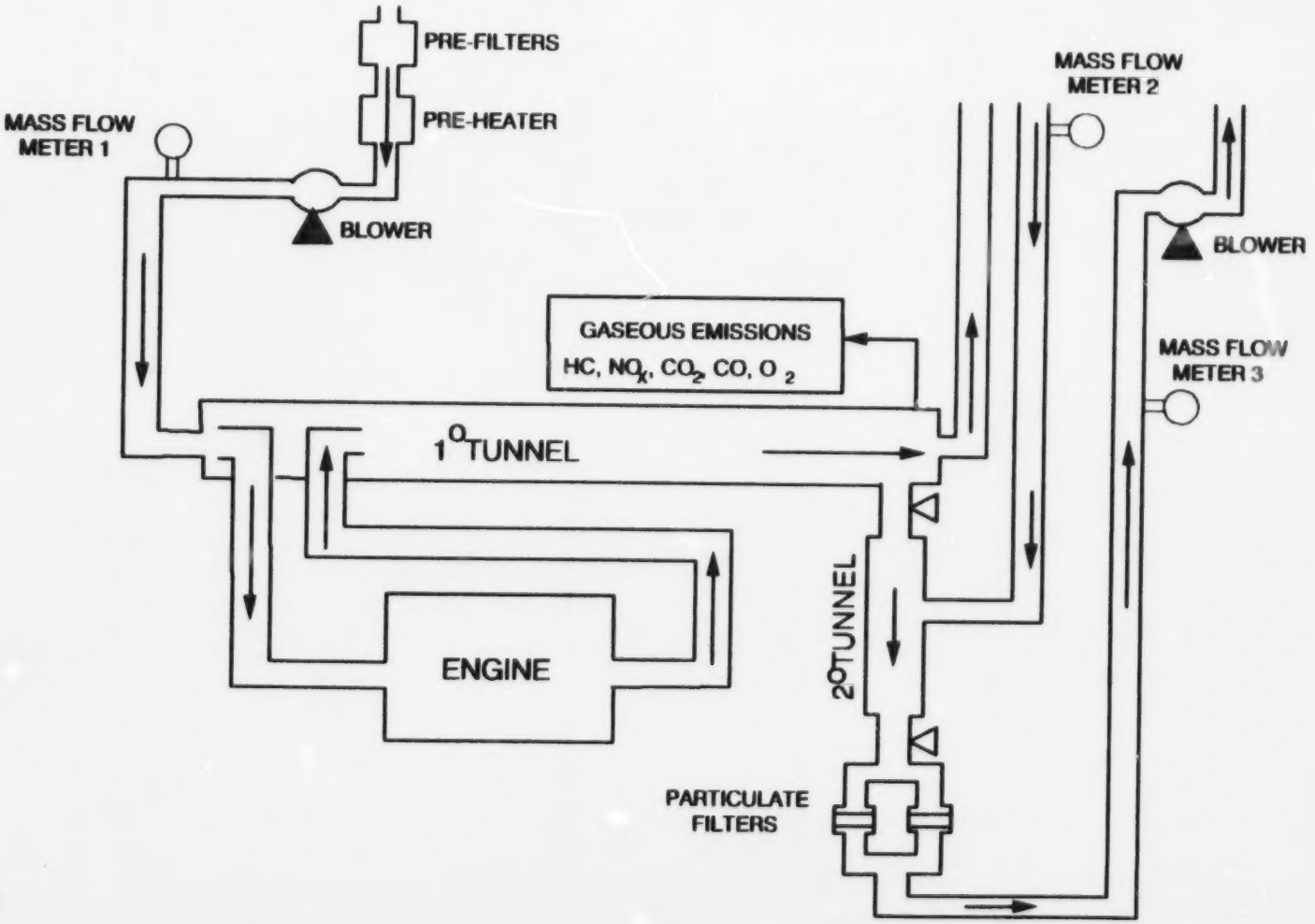
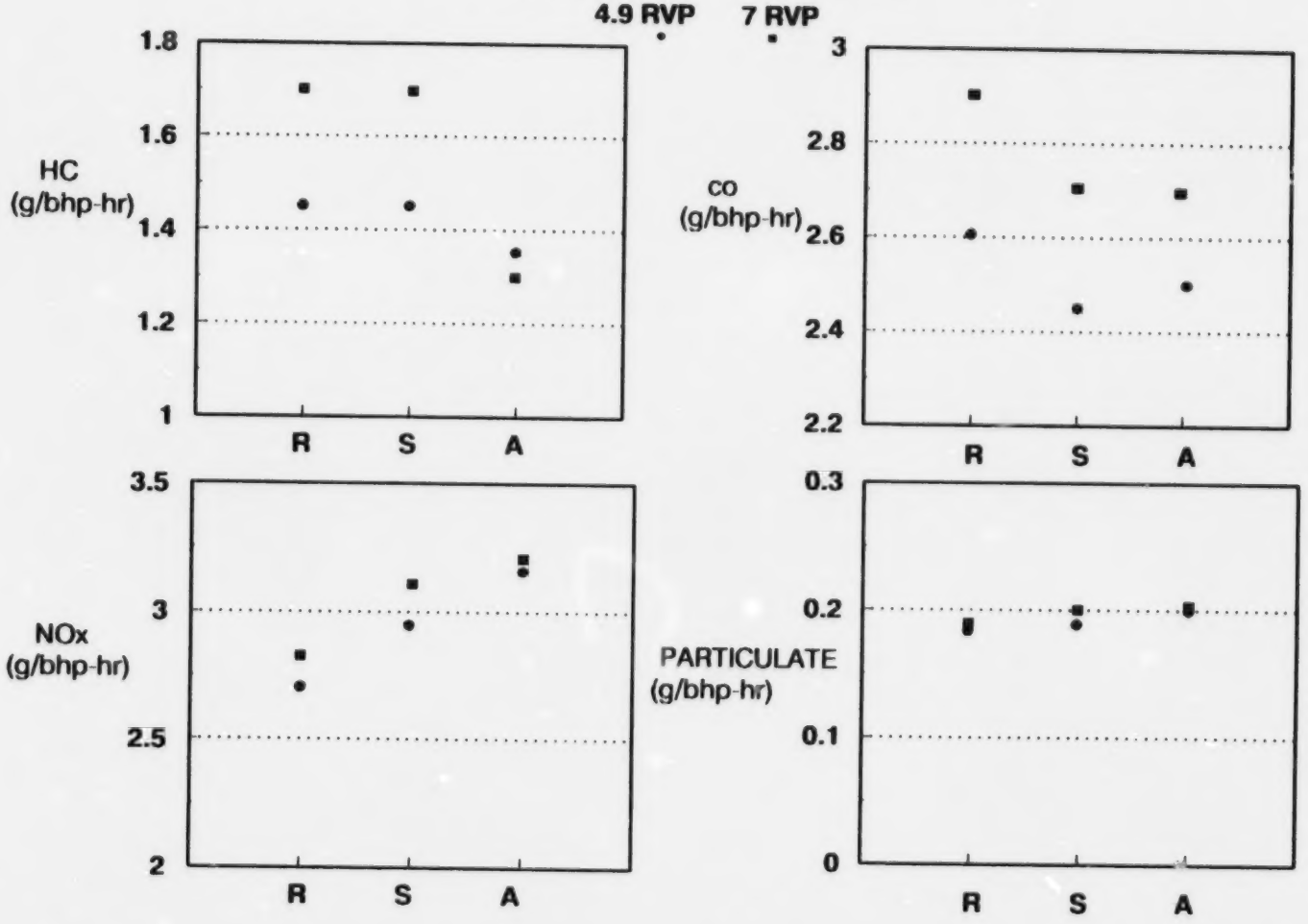
FIGURE 1

DIESEL GASEOUS AND PARTICULATE EMISSION SAMPLING SYSTEM



DWH188S1

FIGURE 2
INCREASING RVP DID NOT REDUCE PARTICULATE,
BUT IT INCREASED HC EMISSIONS

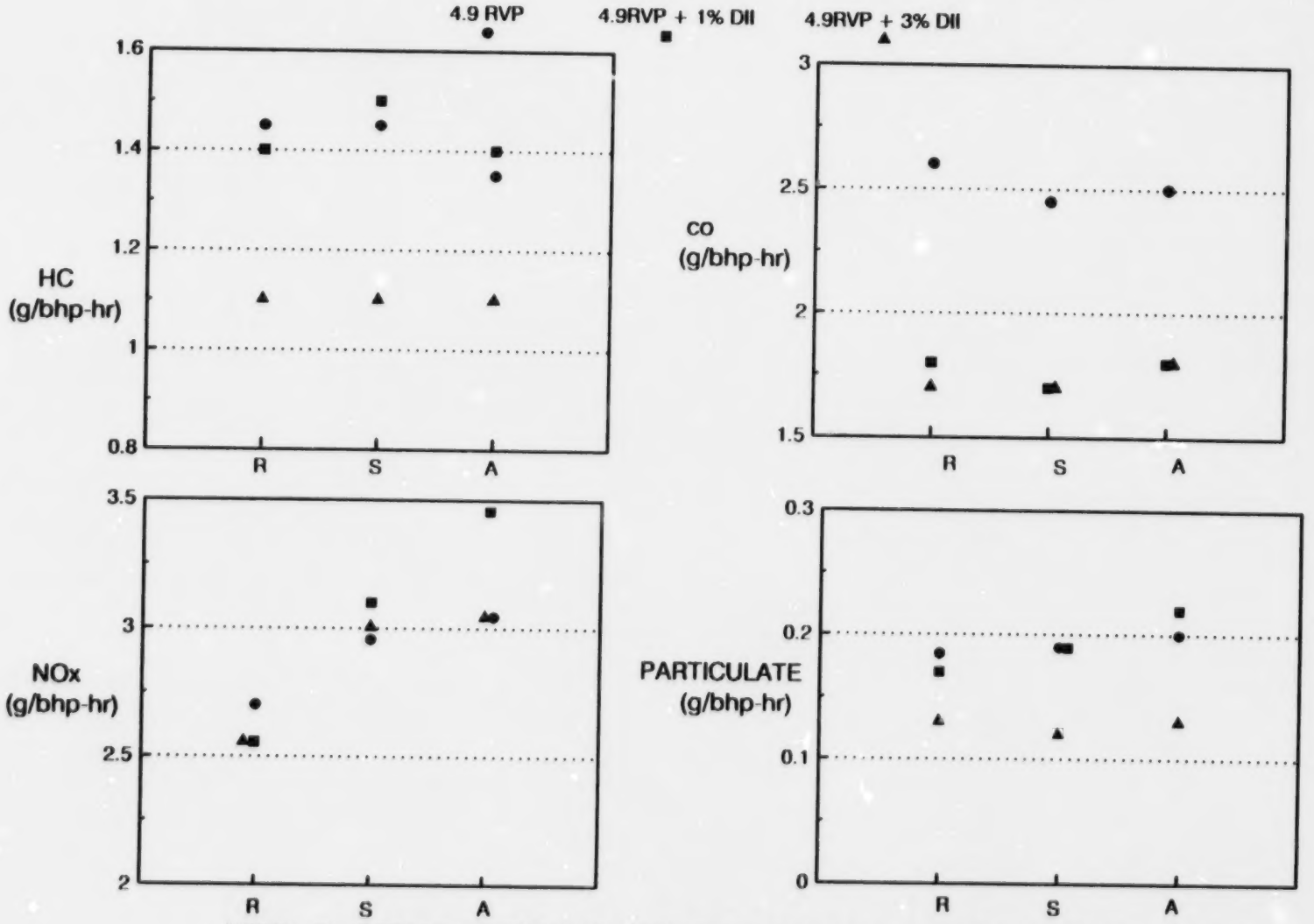


NOTE: R= RETARDED TIMING; S= STANDARD TIMING; A= ADVANCED TIMING

WONG2/FU2

FIGURE 3

HIGH LEVELS OF DII REDUCE PARTICULATE EMISSIONS



NOTE: R= RETARDED TIMING; S= STANDARD TIMING; A= ADVANCED TIMING

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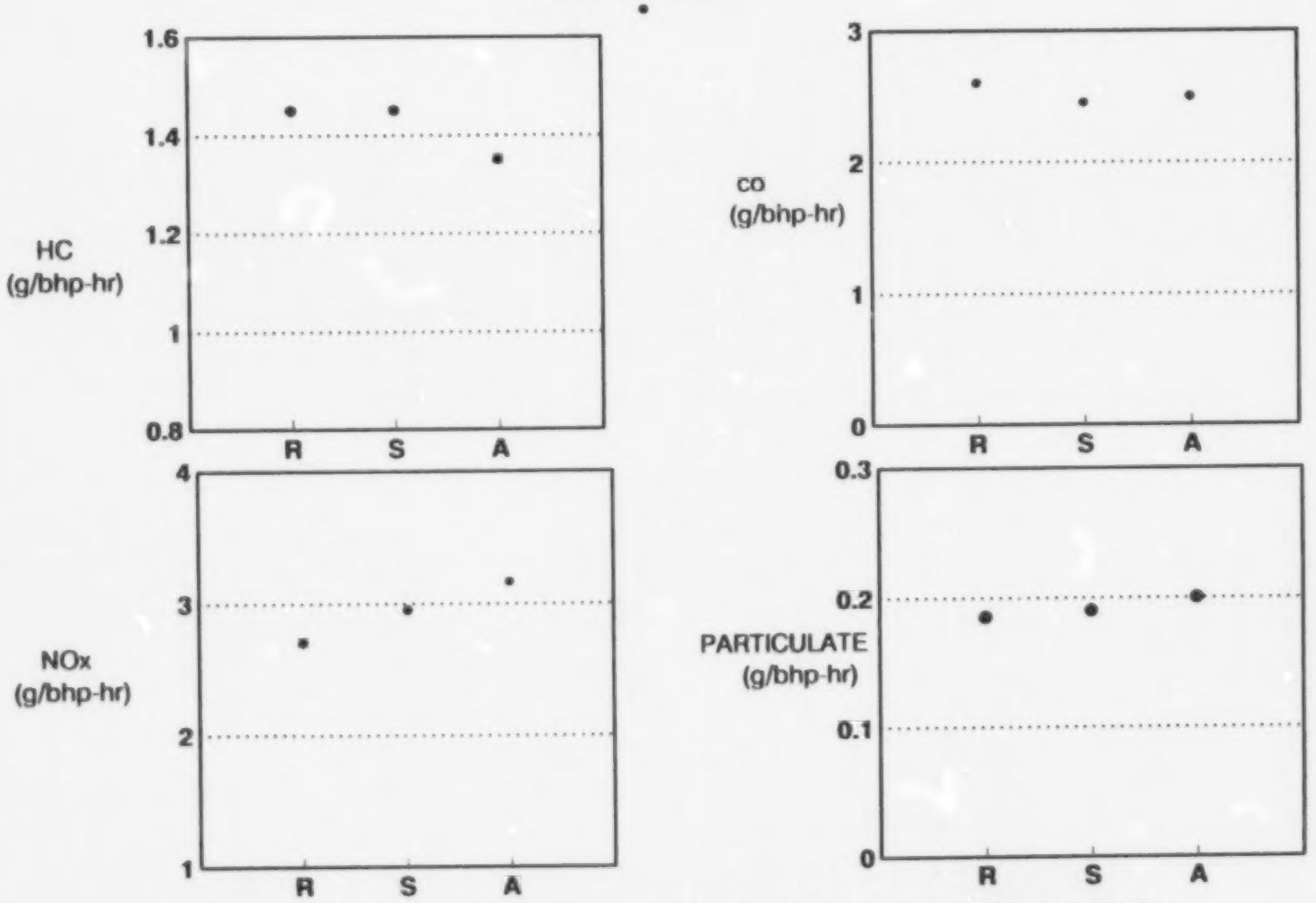
FIGURE 4

FUEL INJECTION TIMING HAVE LITTLE EFFECT ON PARTICULATES

LNN = 4.9 RVP



NOTE: R= RETARDED TIMING; S= STANDARD TIMING; A= ADVANCED TIMING

WONG4/FU2

APPENDIX 1

8 MODE TEST DATA FOR DIESEL FUEL (DATE 90 04 01)

	1	2	3	4	5	6	7	8
Exhaust T, °C	129	207	440	520	247	325	383	430
1° Tunnel, °C	32	40	76	69	66	76	112	139
2° Tunnel, °C	30	35	52	49	51	56	50	48
Particulate Sampling Time (min)	15	10	5	10	10	10	5	5
HC, g/BHP-Hr	3.8	0.7	0.2	0.2	0.8	0.3	0.3	0.3
CO, g/BHP-Hr	9.1	1.9	3.6	8.7	4.0	1.2	1.4	1.8
NO_x, g/BHP-Hr	16.1	8.3	5.5	4.9	1.9	2.6	1.8	2.0
Particulate, g/BHP-Hr	0.28	0.13	0.15	0.19	1.36	0.41	0.18	0.15

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APPENDIX 2

8 MODE TEST DATA FOR DIESEL FUEL (DATE 90 05 15)

	1	2	3	4	5	6	7	8
Exhaust T, °C	130	208	444	522	251	334	395	431
1° Tunnel, °C	32	41	79	75	65	82	123	145
2° Tunnel, °C	29	35	52	46	48	54	50	50
Particulate Sampling Time (min)	10	10	10	5	10	10	5	5
HC, g/BHP-Hr	7.0	1.3	0.3	0.3	1.3	0.6	0.4	0.3
CO, g/BHP-Hr	5.3	1.5	3.4	8.2	3.7	1.3	1.8	1.7
NO_x, g/BHP-Hr	16.1	6.1	4.6	4.6	3.2	2.1	1.8	2.2
Particulate, g/BHP-Hr	0.36	0.15	0.07	0.37	0.85	0.33	0.23	0.15

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APPENDIX 3

8 MODE TEST DATA FOR LNN (4.9 RVP) WITH RETARDED TIMING (1ST TEST)

	1	2	3	4	5	6	7	8
Exhaust T, °C	125	204	448	524	240	336	398	449
1° Tunnel T, °C	32	41	71	77	59	85	123	153
2° Tunnel T, °C	30	35	49	46	49	51	51	56
Particulate Sampling Time (min)	15	10	10	10	10	10	5	5
HC, g/BHP-Hr	9.1	2.7	1.0	0.6	3.8	1.7	0.8	0.5
CO, g/BHP-Hr	14.5	1.5	4.2	5.4	7.2	1.7	1.2	1.0
NO_x, g/BHP-Hr	23.6	8.8	3.4	2.5	2.8	2.5	1.8	1.7
Particulate, g/BHP-Hr	0.27	0.12	0.11	0.13	0.75	0.25	0.15	0.09

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APPENDIX 4

8 MODE TEST DATA FOR LNN (4.9 RVP) WITH RETARDED TIMING (2ND TEST)

	1	2	3	4	5	6	7	8
Exhaust T, °C	122	202	452	528	238	344	401	453
1° Tunnel, °C	31	42	78	80	63	95	138	166
2° Tunnel, °C	28	35	44	48	47	52	49	59
Particulate Sampling Time (min)	15	5	10	5	10	10	5	5
HC, g/BHP-Hr	8.5	1.8	0.6	0.5	8.4	1.5	1.0	0.7
CO, g/BHP-Hr	16.3	1.5	4.4	5.7	10.7	2.4	1.5	0.9
NO_x, g/BHP-Hr	19.7	11.1	3.7	2.9	4.1	2.2	1.5	1.4
Particulate, g/BHP-Hr	0.24	0.19	0.09	0.14	0.72	0.26	0.12	0.09

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APPENDIX 5

8 MODE TEST DATA FOR LNN (4.9 RVP) WITH STANDARD TIMING (1ST TEST)

	1	2	3	4	5	6	7	8
Exhaust T, °C	126	208	448	520	238	333	395	441
1° Tunnel, °C	32	42	71	75	57	80	124	154
2° Tunnel, °C	30	34	51	46	47	50	49	51
Particulate Sampling Time (min)	15	10	10	10	10	10	5	5
HC, g/BHP-Hr	10.1	2.6	0.9	0.7	3.9	1.6	0.8	0.5
CO, g/BHP-Hr	14.5	1.5	4.5	5.1	6.4	1.2	1.3	1.0
NO_x, g/BHP-Hr	29.7	11.2	3.9	2.6	3.2	2.5	1.9	1.8
Particulate, g/BHP-Hr	0.17	0.12	0.09	0.13	0.76	0.19	0.24	0.09

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APPENDIX 6

8 MODE TEST DATA FOR LNN (4.9 RVP) WITH STANDARD TIMING (2ND TEST)

	1	2	3	4	5	6	7	8
Exhaust T, °C	122	200	447	525	240	342	398	443
1° Tunnel, °C	31	43	74	80	62	95	134	160
2° Tunnel, °C	28	34	41	47	45	53	45	56
Particulate Sampling Time (min)	15	5	10	5	10	10	5	5
HC, g/BHP-Hr	8.5	1.8	0.7	0.4	7.8	1.4	1.1	0.7
CO, g/BHP-Hr	16.3	1.5	4.8	5.7	8.5	1.5	1.6	1.0
NO_x, g/BHP-Hr	20.9	12.8	4.3	3.1	4.3	2.3	1.6	1.6
Particulate, g/BHP-Hr	0.21	0.18	0.09	0.15	0.81	0.22	0.13	0.08

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APPENDIX 7

8 MODE TEST DATA FOR LNN (4.9 RVP) WITH ADVANCED TIMING (1ST TEST)

	1	2	3	4	5	6	7	8
Exhaust T, °C	126	209	441	522	238	330	389	433
1° Tunnel, °C	33	41	68	75	57	81	124	145
2° Tunnel, °C	31	35	46	47	48	49	50	53
Particulate Sampling Time (min)	15	10	10	10	10	10	5	5
HC, g/BHP-Hr	9.9	2.5	0.9	0.6	3.8	1.6	0.9	0.5
CO, g/BHP-Hr	21.8	1.5	4.9	6.3	4.4	1.0	1.1	1.0
NO_x, g/BHP-Hr	26.7	17.0	4.7	3.1	4.1	2.3	2.0	1.9
Particulate, g/BHP-Hr	0.16	0.12	0.08	0.13	1.24	0.20	0.15	0.10

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APPENDIX 8

8 MODE TEST DATA FOR LNN (4.9 RVP) WITH ADVANCED TIMING (2ND TEST)

	1	2	3	4	5	6	7	8
Exhaust T, °C	121	204	444	525	239	339	396	437
1° Tunnel, °C	31	44	79	79	63	93	130	158
2° Tunnel, °C	28	36	45	46	48	49	44	52
Particulate Sampling Time (min)	15	5	10	5	10	10	5	5
HC, g/BHP-Hr	8.6	1.8	0.7	0.4	5.5	1.4	1.1	0.6
CO, g/BHP-Hr	23.6	1.1	5.5	6.3	5.5	1.1	1.4	1.5
NO^x, g/BHP-Hr	18.5	17.1	5.2	3.5	5.3	2.4	1.7	1.8
Particulate, g/BHP-Hr	0.20	0.22	0.10	0.13	0.85	0.21	0.14	0.12

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APPENDIX 9

8 MODE TEST DATA FOR LNN (7 RVP) WITH RETARDED TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	120	203	439	545	246	333	389	438
1° Tunnel, °C	34	41	73	88	61	92	134	155
2° Tunnel, °C	32	35	46	52	44	53	47	53
Particulate Sampling Time (min)	15	10	10	5	10	10	5	5
HC, g/BHP-Hr	9.4	1.9	1.1	0.4	11.8	1.4	0.7	0.5
CO, g/BHP-Hr	14.5	1.5	3.2	10.0	8.9	2.4	1.3	0.9
NO^x, g/BHP-Hr	22.1	12.6	3.9	2.3	3.9	2.4	1.7	1.6
Particulate, g/BHP-Hr	0.23	0.14	0.07	0.31	0.53	0.30	0.13	0.10

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APPENDIX 10

8 MODE TEST DATA FOR LNN (7 RVP) WITH STANDARD TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	123	202	438	544	245	330	384	428
1° Tunnel, °C	34	40	71	87	61	90	128	147
2° Tunnel, °C	32	35	44	50	44	51	47	47
Particulate Sampling Time (min)	15	10	10	5	10	10	5	5
HC, g/BHP-Hr	9.0	2.0	1.2	0.4	11.1	1.3	1.0	0.5
CO, g/BHP-Hr	16.3	1.5	4.1	7.9	7.7	1.9	1.3	1.0
NO_x, g/BHP-Hr	26.3	13.9	4.3	2.5	4.2	2.5	1.9	1.8
Particulate, g/BHP-Hr	0.20	0.18	0.09	0.22	0.57	0.39	0.14	0.09

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APPENDIX 11

8 MODE TEST DATA FOR LNN (7 RVP) WITH ADVANCED TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	123	201	436	545	231	326	380	425
1° Tunnel, °C	34	41	73	88	57	89	126	146
2° Tunnel, °C	32	36	47	53	43	51	47	54
Particulate Sampling Time (min)	15	10	10	5	10	10	5	5
HC, g/BHP-Hr	9.2	1.7	0.9	0.4	5.0	1.3	0.8	0.5
CO, g/BHP-Hr	21.8	1.5	4.4	8.2	7.3	1.2	1.1	1.1
NO_x, g/BHP-Hr	17.3	15.1	4.7	2.7	5.2	2.5	2.0	2.1
Particulate, g/BHP-Hr	0.19	0.14	0.07	0.23	0.63	0.37	0.14	0.09

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APPENDIX 12

8 MODE TEST DATA FOR LNN (4.9 RVP + 1% DII) WITH RETARDED TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	129	206	435	525	246	332	392	447
1° Tunnel T, °C	32	41	71	75	60	86	129	155
2° Tunnel T, °C	30	36	41	47	42	51	48	54
Particulate Sampling Time (min)	15	10	10	10	10	10	5	5
HC, g/BHP-Hr	10.3	2.6	0.6	0.2	4.3	1.4	0.8	0.9
CO, g/BHP-Hr	7.3	0.8	2.1	3.1	6.0	1.6	1.2	1.0
NO_x, g/BHP-Hr	25.7	11.8	2.6	1.4	2.5	1.8	1.7	1.6
Particulate, g/BHP-Hr	0.29	0.11	0.06	0.08	0.72	0.23	0.15	0.08

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APPENDIX 13

8 MODE TEST DATA FOR LNN (4.9 RVP + 1% DII) WITH STANDARD TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	128	205	436	525	245	334	388	437
1° Tunnel, °C	33	41	69	75	59	85	123	143
2° Tunnel, °C	31	34	42	47	42	50	46	49
Particulate Sampling Time (min)	15	10	10	10	10	10	5	5
HC, g/BHP-Hr	11.2	2.7	0.6	0.2	4.5	1.6	0.9	0.8
CO, g/BHP-Hr	7.3	0.8	2.7	4.2	4.8	1.0	1.2	1.0
NO_x, g/BHP-Hr	30.4	13.6	3.6	1.8	3.0	2.1	1.9	1.9
Particulate, g/BHP-Hr	0.22	0.11	0.08	0.08	0.79	0.21	0.19	0.10

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APPENDIX 14

8 MODE TEST DATA FOR LNN (4.9 RVP + 1% DII) WITH ADVANCED TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	129	209	435	518	239	331	382	440
1° Tunnel T, °C	32	41	70	74	58	83	120	147
2° Tunnel T, °C	31	37	41	48	42	50	47	52
Particulate Sampling Time (min)	15	10	10	10	10	10	5	5
HC, g/BHP-Hr	9.0	2.6	0.6	0.1	4.3	1.5	0.8	0.9
CO, g/BHP-Hr	7.3	0.8	3.8	4.8	4.0	1.0	1.0	1.3
NO_x, g/BHP-Hr	32.2	21.1	3.6	2.0	3.1	2.3	2.0	2.0
Particulate, g/BHP-Hr	0.19	0.12	0.07	0.08	0.90	0.30	0.22	0.08

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APPENDIX 15

8 MODE TEST DATA FOR LNN (4.9 RVP + 3% DII) WITH RETARDED TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	121	208	449	529	246	328	389	444
1° Tunnel, °C	29	42	77	76	58	81	119	153
2° Tunnel, °C	26	35	47	47	45	46	39	51
Particulate Sampling Time (min)	15	10	10	5	10	10	5	5
HC, g/BHP-Hr	7.6	2.2	0.8	0.5	3.4	1.4	0.7	0.4
CO, g/BHP-Hr	5.4	1.5	2.8	5.0	2.6	0.9	1.4	1.0
NO_x, g/BHP-Hr	22.1	8.1	3.8	2.8	2.5	2.2	1.7	1.6
Particulate, g/BHP-Hr	0.24	0.09	0.06	0.08	0.54	0.14	0.11	0.06

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APPENDIX 16

8 MODE TEST DATA FOR LNN (4.9 RVP + 3% DII) WITH STANDARD TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	126	207	449	533	243	331	384	442
1° Tunnel, °C	32	42	77	76	59	82	116	149
2° Tunnel, °C	29	36	47	48	44	47	36	47
Particulate Sampling Time (min)	15	10	10	5	10	10	5	5
HC, g/BHP-Hr	8.3	2.3	0.8	0.4	3.2	1.3	0.7	0.4
CO, g/BHP-Hr	5.4	1.5	3.5	5.3	2.1	0.9	1.3	1.0
NO_x, g/BHP-Hr	28.0	10.8	4.0	3.4	2.9	2.0	1.8	1.8
Particulate, g/BHP-Hr	0.30	0.08	0.06	0.08	0.49	0.14	0.11	0.07

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APPENDIX 17

8 MODE TEST DATA FOR LNN (4.9 RVP + 3% DII) WITH ADVANCED TIMING

	1	2	3	4	5	6	7	8
Exhaust T, °C	124	210	449	535	239	326	381	437
1° Tunnel, °C	31	46	77	77	58	80	116	147
2° Tunnel, °C	28	37	47	47	44	46	37	49
Particulate Sampling Time (min)	15	10	10	5	10	10	5	5
HC, g/BHP-Hr	8.3	2.3	0.7	0.4	3.3	1.2	0.7	0.4
CO, g/BHP-Hr	7.3	1.1	4.5	5.0	2.1	0.9	1.2	1.3
NO_x, g/BHP-Hr	25.7	15.5	4.4	3.1	3.4	1.8	1.9	1.9
Particulate, g/BHP-Hr	0.26	0.08	0.06	0.08	0.55	0.18	0.12	0.07

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